SUMMARY TALK AT THE 3^{rd} KEK TOPICAL CONFERENCE ON CP VIOLATION

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A summary of the contributions to this topical conference is presented. The topics discussed ranged from detailing what we know about CP violation, to what we hope to learn in the future, to still unsolved mysteries in the subject.

1. Introduction

Reflecting on how to summarize the many interesting and lively contributions made in the 3^{rd} KEK Topical Conference on CP Violation, I decided to divide my remarks into three categories:

i) What do we know about CP violation

ii) What are we likely to learn in the future

iii) The mysteries.

I believe both the subject matter and the various talks we heard during this Topical Conference nicely fit in one of these categories. Furthermore, by proceeding in this way it allows me to follow the well established tradition of scientific discourse, where one starts on solid ground, proceeds to a more speculative level and ends by discussing things in which one has no clear understanding at all!

2. What do we know about CP violation

The study of CP violation is now 30 years old and thus certainly is a mature subject. Nevertheless, we still have very limited experimental information information on this phenomena:

i) Our only positive evidence for CP violation is in the neutral Kaon system, where we have measurements of two complex ratios η_{+-} and η_{oo} and of the semileptonic K_L symmetry, A_{K_L}.

ii) We have, however, a variety of bounds on possible other CP violating phenomena, most notably very stringent bounds on the electric dipole moment of the neutron and of the electron [1].

iii) Furthermore, one can adduce evidence from astrophysics and cosmology that CP violating phenomena played an important role in the evolution of our universe. In particular, the ratio of baryon to photons in the universe now $n_B/n\gamma \sim 4 \times 10^{-10}$ [2] is a measure of CP violation, if the baryon asymmetry in the universe is generated dynamically [3].

Both the evidence for CP violation in the neutral Kaon system, as well as the bounds on the neutron and electron dipole moments, are consistent with the Cabibbo Kobayashi Maskawa (CKM) paradigm [4], where CP violation arises as a result of having a complex quark mixing matrix. It is likely, however, that the baryon to photon ratio is connected with a different source of CP violation, lying beyond the standard model. I would like to expand on the first of these statements here and I will return to the second point towards the end of this talk.

Qualitatively the measured CP violating parameters in the neutral K-system can be summarized by the following observations:

i) The dominant source of CP violation comes as a result of $K-\bar{K}$ mixing ($\Delta S = 2$ CP

violation). Thus

$$\eta_{+-} = \epsilon + \epsilon' \simeq \eta_{oo} = \epsilon - 2\epsilon' \quad ,$$

since the $\Delta S = 1$ CP-violating parameter ϵ' is much smaller than the $\Delta S = 2$ CP violating parameter ϵ.

ii) The width matrix in the $K - \bar{K}$ system is dominated by the 2π intermediate state and CPT is conserved. This circumstance leads to the following two relations [5], which are well satisfied experimentally

$$A_{K_L} \simeq 2Re\eta_{+-} \ ,$$

$$\phi_{+-} \simeq \phi_{SW} = \tan^{-1} \frac{2\Delta m}{\Gamma_S - \Gamma_L} \simeq 45^o \ .$$

The CKM paradigm provides a semiquantitative explanation of the first of these observations, while (assuming CPT conservation) the second set of results follows essentially kinematically, given the strong $\Delta I = 1/2$ enhancement of the 2π channel. Indeed, this enhancement is also partly responsible for the reason why CP violation due to mixing is much greater than that due to $\Delta S = 1$ processes (direct CP-violation). However $\epsilon' \ll \epsilon$ follows also because the $\Delta S = 1$ processes are Zweig-rule violating processes, involving electromagnetic or gluonic Penguin contributions [6]. Schematically, one finds in the CKM model that [7]

$$\frac{\epsilon'}{\epsilon} \sim \frac{ReA_2}{ReA_0} \left[\frac{\alpha_s}{12\pi} \ell n \ m_t^2/m_c^2 \right] \sim 10^{-3} \quad ,$$

where the first factor above contributes the $\Delta I = 3/2$ to $\Delta I = 1/2$ suppression of about 1/20. Furthermore, the CKM model also provides a qualitative understanding of why ϵ is of $O(10^{-3})$ without having to appeal to the presence of a small CP violating phase. Again, qualitatively, one has in the case of 3 generations [7]

$$\epsilon \sim \frac{ImM_{12}}{ReM_{12}} \sim \frac{s_{12}s_{23}s_{13}\sin\delta}{s_{12}^2} \sim 10^{-3}\sin\delta \ .$$

That is, ϵ is small because the product of mixing angles entering in the box graph contributing to this parameter is already experimentally of $O(10^{-3})$, independent of what the phase δ is.

It turns out that the CKM model also provides a qualitative explanation for why no electric dipole moment for the neutron has been observed. It is easy to convince oneself that there is no one-loop contribution to the edm, since all the phase information cancels. Remarkably, [8] in the CKM model also the sum of all two-loop graphs cancels, so that the first non-trivial contribution arises at the three-loop level. This contribution can be estimated to be of order [7]

$$d_n \sim e \ m_d \frac{\alpha^2\alpha_s}{\pi^3} \frac{m_t^2 m_b^2}{M_W^6} s_{12}s_{23}s_{13}\sin\delta \sim 10^{-32} ecm$$

which is many orders of magnitude below the present bound [1].

Since the experimental value of ϵ (or η_{+-}) just fixes the value of the CP phase δ-assuming the mixing angles are known precisely (see below for a more detailed discussion) – the value of ϵ' is the only quantitative test of the CKM model available at present. However, as we learned from the talk of Tschirhart, [9] the experimental situation remains inconclusive, because the CERN and FNAL experiments do not quite agree on what ϵ' is. One has

$$Re\frac{\epsilon'}{\epsilon} = \begin{cases} (23 \pm 7) \times 10^{-4} & \text{[NA31]} \\ (7.4 \pm 5.9) \times 10^{-4} & \text{[E731]} \end{cases}$$

Futhermore, as Reina [10] showed, the theoretical calculation of this ratio still has rather large hadronic matrix element uncertainties, and also suffers from a lack of accuracy in the knowledge of the values of the relevant CKM matrix elements. Although the best theoretical analysis of the problem seems to favor the lower Fermilab value (see below), it is really too early to make a definite pronouncement on this score.

Irrespective of theoretical prejudices, it is important to resolve in the Kaon system the experimental controversy regarding ϵ'/ϵ. A clear measurement of a non zero value for ϵ' would provide the first proof of the existence of direct CP violation – something that if one believes in the CKM paradigm one knows must exist! A measurement of ϵ'/ϵ to the level of 10^{-4} should emerge in the next round of CP violation experiments at CERN and Fermilab [9] and possibly from the Frascati Φ

Table 1
Prospects and Expectations for CP Violation Tests in Rare Decays [12]

Process	CKM Expectations	Experimental Prospects
$K_S \to 3\pi^0$	$\epsilon'_{000}/\epsilon \sim 10^{-2}$	$\delta\eta_{000} \sim 4 \times 10^{-3}$
$\eta_{000} = \epsilon + \epsilon'_{000}$		[Φ Factory]
$K^\pm \to \pi^\pm\pi^\mp\pi^\pm$	$\Delta\Gamma \leq 10^{-6}$	$\delta(\Delta\Gamma) \sim 5 \times 10^{-5}$
$\Delta\Gamma = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}$	$\Delta g \leq 10^{-4}$	$\delta(\Delta g) \sim 5 \times 10^{-4}$
$\Delta g = \frac{g_+ - g_-}{g_+ + g_-}$		[Φ Factory]
$K^\pm \to \pi^\pm\pi^0\gamma$	$\Delta\Gamma \sim 10^{-3} - 10^{-5}$	$\delta(\Delta\Gamma) \sim 2 \times 10^{-3}$
$\Delta\Gamma = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}$		[Φ Factory]
$K_L \to \pi^0\ell^+\ell^-$	$B_{\rm direct} \sim 10^{-11} - 10^{-13}$	$B \leq 7 \times 10^{-11}$
$B(K_L \to \pi^0\ell^+\ell^-)$		[KTeV; NA48]
$K_L \to \pi^0\nu\bar{\nu}$	$B \sim 10^{-12}$	$B \sim 10^{-8} - 10^{-9}$
$B(K_L \to \pi^0\nu\bar{\nu})$		[KTeV]

Factory [11]. Other precision experiments using both charged and neutral Kaons, which are now in the planning stage, potentially have bearing on whether direct CP violation exists. However, as Table 1 shows, these experiments are unlikely to reach the required level of sensitivity [9][11]

I should comment that it is quite important also to try to pursue experiments which are particularly sensitive to non-CKM sources of CP violation. A well-known example is offered by attempts to measure an electric dipole moment for the neutron. Two other nice examples were discussed in this Conference. Shimizu[13] reported on an ongoing experiment at KEK aimed at looking for T-violation in slow neutron capture in a polarized ^{134}La target. Values of the triple correlation parameter

$$\lambda \sim \langle \vec{\sigma}_n \cdot (\vec{k} \times \vec{I}_{La}) \rangle$$

down to $\lambda \sim 10^{-2}$ should be accessible in this experiment, which in sensitivity compares to a measurement of the neutron edm to $d_n \sim 5 \times 10^{-24}$ ecm. A second experiment discussed here by Y. Kuno [14] – and whose theoretical implications were illustrated by C. Geng [15] – concerns measuring the transverse muon polarization in charged K decay ($K^+ \to \pi^o\mu^+\nu_\mu$). This polarization again is proportional to a triple correlation

$$\langle p_T \rangle \sim \vec{\sigma}_\mu \cdot (\vec{p}_{\pi^o} \times \vec{p}_\mu)$$

and is sensitive to a possible effective scalar weak interactions, such as those induced by an extended Higgs sector. Writing this effective scalar interaction as

$$M_{\rm eff} \simeq G_F \sin\theta_c m_K \xi \bar{\mu}(1-\gamma_5)\nu_\mu \ ,$$

through a measurement of $\langle P_T \rangle$ the E246 experiment at KEK should be sensitive to values of $Im\xi$ down to $\delta Im\xi = 2 \times 10^{-3}$. Such a measurement, particularly if there is a light charged Higgs, is much more sensitive to possible CP violating phases in the Higgs sector than a direct measurement of d_n [15].

Even though it is important to test for non CKM CP violating phenomena, clearly a dominant theme in the study of CP violation in the future will remain trying to ascertain how well the CKM paradigm actually works. For these purposes, in my view, the more relevant tests will occur not in the Kaon system but in the decay of neutral B's to CP-self conjugate final states. To understand the expectations of the CKM model for these decays, it will be useful for me to enter into a bit of detail on what is known about the CKM matrix itself.

It is convenient to write the CKM matrix in the Wolfenstein form [16], where the three mixing angles are expanded in terms of powers of the Cabibbo angle, $\sin\theta_c \simeq \lambda \simeq 0.22$. One has [16]

$$\sin\theta_{12} = \lambda \quad \sin\theta_{23} = A\lambda^2 \quad \sin\theta_{13} = A\sigma\lambda^3 \,.$$

As we shall see, experimentally both A and σ are of $O(1)$. In terms of the above, to $O(\lambda^3)$ the CKM matrix can be written as

$$V_{\rm CKM} = \left| \begin{array}{ccc} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\sigma e^{-i\delta} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\sigma e^{i\delta}) & -A\lambda^2 & 1 \end{array} \right| .$$

Often, instead of σ and the CP violating phase δ, one uses instead the parameters ρ and η with

$$\sigma e^{i\delta} = \rho - i\eta \,.$$

Experimentally A, which is related to V_{cb}, is knows to about 10%, while both σ and δ, or ρ and η, are known to only about 30%. These errors, however, are **not** measurement errors, but arise from trying to extract theoretically these parameters from experiment. These uncertainties were discussed in considerable detail in this Conference. The parameter A is extracted from semileptonic B decays, either through an inclusive analysis or by focusing on some particular exclusive mode. In the former case, one needs to remove the sensitivity of the rate on the uncertain m_b mass ($\Gamma \sim m_b^5!$). For the exclusive case, heavy quark effective theory (HQET) determines the form factors at zero recoil for the process $B \to D^*\ell\nu$ [17]. However one needs to extrapolate the data to this point, which induces in general uncertainties. (For a contrary opinion, see M. Tanaka [18] in these proceedings). Using a new average value for the B lifetime, mostly determined by LEP data and by CDF data,

$$\langle\tau_B\rangle = 1.535 \pm 0.025 \;\; ps \;,$$

M. Witherell [19] in this Conference concluded from a combined fit of the Cleo semileptonic data that

$$|V_{cb}| = 0.042 \pm 0.001 \pm 0.004 \;.$$

Here the last error is an estimate of the model dependence of the results. The equivalent value obtained by extrapolating to the zero recoil point the data for the exclusive $\bar{B}^o \to D^{*+}\ell^-\nu$ decay measured by Argus and Cleo gives [19]

$$|V_{cb}| = 0.040 \pm 0.006$$

The average of these two determinations [19] yields

$$|V_{cb}| = 0.041 \pm 0.005 \quad \text{or} \quad A = 0.85 \pm 0.10$$

One can perhaps imagine reducing the above error to the 5% level in the future. For the inclusive analysis, the model dependence of the results can be alleviated since corrections to the parton model results are under control, via a combination of a QCD operator product expansion and a $1/m_b$ expansion [20]. Furthermore, more data for the process $B \to D^*\ell\nu$ should allows a better extrapolation to be done in the exclusive analysis.

This optimism, however, is not quite warranted for the case of $\sigma = \sqrt{\rho^2+\eta^2}$. This parameter is related to $|V_{ub}|$. First of all, at the moment, we still do not have any uncontroversial indications for an exclusive signal, like $B \to \rho\ell\nu$. Furthermore, for the inclusive case, to see evidence for V_{ub} one must look very near the kinematic end point for the electron spectrum in semileptonic B decays, since beyond $P_\ell = 2.3 \;\; GeV$ the decay $B \to X\ell\nu$, with X containing a charmed state, is kinematically forbidden. Using the recent data from Cleo for leptons beyond the charm end point, Witherell[19] arrives at the following two values for $|V_{ub}|/|V_{cb}|$, depending on whether he extracts this value from the data by using a partonic approach [ACM model [21]] or whether he sums over exclusive final states [IGSW model [22]]:

$$\frac{|V_{ub}|}{|V_{cb}|} = \lambda\sigma = \left\{ \begin{array}{l} 0.076 \pm 0.008 \; [ACM] \\ 0.101 \pm 0.010 \; [IGSW] \end{array} \right.$$

Expanding the theoretical uncertainty somewhat, this analysis leads to a value for the CKM matrix element ratio

$$|V_{ub}|/|V_{cb}| = 0.085 \pm 0.025 \quad \text{or} \quad \sigma = 0.38 \pm 0.11$$

In this Conference, C. S. Kim [23] presented a thorough analysis of the model dependence of the results for $|V_{ub}|/|V_{cb}|$. For this ratio one is

really much more dependent on models, since it is difficult to apply the QCD operator expansion technique as one has no longer a controlled $1/m_b$ expansion. Rather, the expansion

Fig. 1. Allowed region in the $\rho-\eta$ plane. Also shown in the figure are what parameters determine the boundary of this region.

parameter because of soft gluon emission, here is more like $1/m_b(1-E_e/E_{\rm max})$ which fails near the end point[24]. It is a very crucial question– and one of much current interest – whether one can avoid these difficulties somehow and obtain a more reliable estimate for σ.

Information on the CP violating phase δ comes, of course, from the measured value for ϵ. However, since δ also enter in V_{td}, one can obtain some restriction on this parameter from the observed $B_d-\overline{B}_d$ mixing parameter x_d, which is proportional to $|V_{td}|^2$. Again, there are theoretical uncertainties here related to the poor knowledge of the hadronic matrix element connected with $|\epsilon|$ and $|x_d|$. The former is characterized by the, so-called, B_K parameter, which lattice computations give to a 20% accuracy [$B_K=0.8\pm0.2$ [25]]. For x_d the relevant parameter [7] is an effective B-decay coupling constant, which is again best determined through lattice computations [25]

$$f_B^{eff}=\sqrt{B_B\eta_B}f_B=(200\pm35)MeV$$

Because of these matrix element uncertainties, the rather precisely measured values for $|\epsilon|$ and x_d give allowed bands in the $\sigma-\delta$ or $\rho-\eta$ plane. As an illustration, the overlap of these bands with the region allowed by our present (imperfect) knowledge of $\sigma=\sqrt{\rho^2+\eta^2}$ is shown in Fig. 1, assuming $m_t=140$ GeV. One sees from this figure that the physically allowed values for ρ and η in the CKM model are now constrained to a rather small region in the $\rho-\eta$ plane.

I will return below to discuss the implications of Fig. 1 for CP violation in B decays. I note here only that, for m_t=140 GeV, using my guesstimate of the calculations presented by Reina[10] for the matrix element involved in ϵ'/ϵ one has

$$\epsilon'/\epsilon=(11\pm4)\times10^{-4}A^2\eta\ .$$

Fig. 1 makes apparent that the expected value for ϵ'/ϵ in the CKM model favors the result obtained by the Fermilab E731 experiment. [9]

3. What are we likely to learn in the future?

One should see considerable clarification of the nature of CP violation in the coming years. In the Kaon sector, as Tschirhart[9] and Bertolucci[11] discussed, new experiments at FNAL [KTeV] and at CERN [NA48], as well as at the Frascati Φ Factory [KLOE], should push the error on ϵ'/ϵ to $O(10^{-4})$. However, the next round of rare K decays which are sensitive to the phase δ of the CKM matrix [cf. Table 1] will only set limits rather than provide a new measurement for this phase.

Even though the efforts to uncover CP violating phenomena in the Kaon sector are impressive, it is clear that much of the future experimental activity will be focussed in the B sector. After a long struggle, not one but two asymmetric B-factories will begin construction in 1994 and are aiming to take first data in 1998. Although nobody at this Conference discussed in detail the SLAC B factory, the talk by Abe[26] on the KEK project served to give an indication of the general characteristics of these facilities. The KEK B-factory will have two new rings in the existing Tristan tunnel, with 3.5 GeV positrons and 8 GeV electrons directly injected into these storage rings. The beams will cross at an angle of 2.8 mrad and the machine parameters are de-

signed so as to achieve an initial luminosity of $\mathcal{L} = 2 \times 10^{33}\ cm^{-2}\ sec^{-1}$. Eventually, by increasing the beam current, at KEK one hopes to achieve $\mathcal{L} = 10^{34}\ cm^{-2}\ sec^{-1}$. As we shall see, this high luminosity is necessary if one wants to insure the full reach for measuring the CP violation asymmetries expected in the B sector in the CKM model.

It was clear at the Conference, however, that considerable other activity is also going on in the world in B-physics. Indeed, through the 1990's much will be learned about the B system from experiments at LEP and at the Fermilab Collider and, particularly, at the CESR ring in Cornell. This was nicely illustrated in the talks of Witherell[19] and Lockeyer [27]. As an example of the nice results obtained, Witherell showed evidence at the 10^{-5} BR level for the important 2-body decay mode $B \to \pi\pi/K\pi$ measured at CESR (the CLEO II data cannot yet distinguish among these two possibilities, for lack of statistics). Lockeyer showed a clear discovery signal for the B_s meson, through the decay $B_s \to \psi\phi$, seen by CDF. These results, besides their intrinsic value, are also important "engineering" information for efforts to study CP violation and $B_s - \bar{B}_s$ mixing at both electron and hadronic colliders.

Lockeyer's talk at the Conference [27] made it clear that hadronic colliders can be very competitive and complementary to the e^+e^- B-factories in this respect, because the more difficult experimental environment of hadron machines can be compensated by the enormous rate for B production. For instance, with the main injector luminosity, there will be about 10^{11} B's produced per year at the Fermilab Collider, while at the LHC one will have over 10^{12} B's/year. Because of these high rates, a very active program of experiments for the year 2000 and beyond are now being considered. Fermilab has called for new collider expressions of interests by May 1994 and the LHC experiments committee will be examining three LOI for dedicated B detectors in the same time frame. How competitive all of these efforts will be to the B factories will depend (besides on schedules!) on the ability to make progress on triggering on certain modes (e.g. $B_d \to \pi^+\pi^-$) and on B-tagging in the harsh hadronic environment.[27]

The detailed physics which will be pursued at the B factories and in the hadronic colliders was discussed at this Conference by H. Quinn[28]. Fundamentally what one wants to check first is whether the CKM paradigm is correct. This can be done best in the neutral B system by testing the, so called, unitarity triangle[29]. Of course, this is not the only place where one can look for CP violating effects in the B system. However, both in charged B decays–discussed in this Conference by Hou[30] –or in radiative B decays, like $B \to K\pi\gamma$–discussed here by Soni[31]–the actual expectations for CP violating phenomena are much more dependent on hadronic dynamics and even the cleanest cases are often rather rate limited.

The unitarity of the 3 generation CKM matrix implies for the $d - b$ piece that

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

or, approximately, to $O(\lambda^3)$

$$V_{ub}^* + V_{td} \simeq \lambda V_{cb}^* = A\lambda^3 \ .$$

Since $V_{ub}^* \simeq A\lambda^3\ (\rho + i\eta)$ and $V_{td} = A\lambda^3\ (1 - \rho - i\eta)$, one sees that the unitarity of the CKM matrix gives one a triangle in the $\rho - \eta$ plane. This triangle has a base going from $\rho = 0$ to $\rho = 1$ and its apex is any of the points (ρ, η) which are allowed in Fig. 1. Remarkably, the three angles in this "unitary triangle"[29] are in principle measurable in B decays to CP self-conjugate states[32]. Hence these decays should provide a direct test of the CKM paradigm. As shown in Fig. 2 the angle β spans a much narrower range than the angles α and γ. For example, for $m_t = 140$ GeV one has $16° \leq \beta \leq 27°$.

Fig. 2. Two examples of unitarity triangles allowed by the CKM paradigm for $m_t = 140$ GeV.

The angles α, β and γ in the unitarity triangle can be extracted by measuring asymmetries in the decay of neutral B mesons to self-conjugate final states f, where $\bar{f} = \eta_f f$ with $\eta_f = \pm 1$. As Quinn[28] showed, a state born at $t = 0$ as a B meson which decays into a final state f, has a different time evolution than a state which at $t = 0$ was a $\bar{B}$. One finds, under the assumption that only one weak amplitude dominates[32]:

$$\begin{aligned}\Gamma\ (B_{\rm phys}(t) \to f) &= \Gamma(B \to f) \\ &\times\ e^{-\Gamma t}\{1 - \eta_f \lambda_f \sin \Delta m t\}\end{aligned}$$

$$\begin{aligned}\Gamma(\bar{B}_{\rm phys}(t) \to f) &= \Gamma(B \to f) \\ &\times\ e^{-\Gamma t}\{1 + \eta_f \lambda_f \sin \Delta m t\}\end{aligned}$$

Here λ_f contains information about CP violation. In the CKM model λ_f depends directly on the angles of the unitarity triangle and one finds

$$\lambda_f = \begin{cases} \sin\ 2\alpha & \text{for } B_d \text{ decays involving a } b \to u \text{ transition} \\ \sin\ 2\beta & \text{for } B_d \text{ decays involving a } b \to c \text{ transition} \\ \sin\ 2\gamma & \text{for } B_s \text{ decays involving a } b \to u \text{ transition} \\ 0 & \text{for } B_s \text{ decays involving a } b \to c \text{ transition} \end{cases}$$

The prototype decay for measuring the angle β is the decay $B_d \to \psi K_S$. Given the allowed region in the $\rho - \eta$ plane of Fig. 1, the relevant asymmetry between the rates of $(B_d)_{\rm phys}$ and $(\bar{B}_d)_{\rm phys}$ into this mode is very large [e.g. for $m_t = 140$ GeV, one has $0.53 \leq \sin\ 2\beta \leq 0.81$]. Furthermore, for the decay $B_d \to \psi K_S$ the assumption of having only one (effective) weak amplitude is well justified [33], since in this case both the weak transition $b \to c\bar{c}s$ and the associated Penguin amplitude have the same weak phase. Thus this decay mode has excellent theoretical prospects. As Abe[26] discussed in his talk, the process $B_d \to \psi K_S$ is also fine from an experimental point of view. Using the leptonic decays of the ψ and the charged pion decays of the K_S, Abe estimates that with an integrated luminosity of 100 fb^{-1} the error in $\sin\ 2\beta$ at the KEK B factory should be $\delta \sin\ 2\beta = 0.081$. Obviously, this measurement would suffice to establish that $\sin\ 2\beta$ is non-vanishing, if it is in the range expected in the CKM model. Furthermore, this is not the only decay of B_d states in which $sin\ 2\beta$ is accessible[28]. Indeed, as Hall[34] commented, it is likely that besides the Cabibbo angle and V_{cb}, $\sin\ 2\beta$ will eventually be the next best known weak parameter connected to the CKM matrix.

The angle α, whose prototype decay is $B_d \to \pi^+\pi^-$, appears to be much harder to pin down. In principle, for the case of $B_d \to \pi^+\pi^-$ the Penguin amplitude has a different phase than the decay amplitude, and so this decay is not theoretically pristine. However, the fact that likely [19]

$$BR(B_d \to \pi K) \simeq BR(B_d \to \pi\pi)$$

may alleviate this problem, since $B_d \to \pi K$ is purely Penguin dominated and the $b \to s$ Penguin contribution should be much bigger than the $b \to d$ Penguin contribution. So, effectively, also for $B_d \to \pi^+\pi^-$ one probably has only one dominating weak amplitude. At any rate, as Quinn[28] discussed, one can in principle disentangle this issue by doing a Dalitz analysis of the decay $B_d \to \rho\pi$. What is more troubling is that the allowed unitarity triangles permits the value $\alpha = 90^\circ$ (see Fig. 2) and thus the asymmetry in this case is not necessarily large. In fact, as Nir[35] and others have emphasized, any value for

sin 2α is consistent with what we presently know about the CKM matrix. At a B factory, assuming that $BR(B_d \to \pi^+\pi^-) = 2 \times 10^{-5}$, the relevant error on sin 2α, again with 100 fb^{-1} of data, is about twice as large as that for $B_d \to \psi K_S$ ($\delta \sin\ 2\alpha = 0.17$[26]). So it remains to be seen if one can make a clear measurement of this angle.

The angle γ is even harder to determine. First of all, to study it most simply one needs to measure B_s decays and these will not be accessible at the asymmetric B factories. However, prototype decays like $B_s \to \rho K_S$ do suffer from "Penguin pollution"[33] and may not be theoretically pristine enough. As Gronau and London[36] emphasized, it is possible to extract γ by studying B_d decays to non CP self-conjugate states, like $B_d \to D^o K^*$. However, then one is forced to compare different processes and the prospects for an accurate determination are not very sanguine[28].

In my view, measuring a large asymmetry connected with sin 2β in B decays will go a long way towards establishing the validity of the CKM paradigm. It is of course true that, accidentally, the rate difference between $(B_d)_{\rm phys} \to \psi K_S$ and $(\bar{B}_d)_{\rm phys} \to \psi K_S$ could be large in a non CKM context, but it would be a remarkable coincidence. This said, however, as Quinn[28] emphasized here, it is important to check that the unitarity triangle actually closes. For instance, as Branco[37] discussed in his talk, it is relatively easy to change the mixing phase in the $B_d - \bar{B}_d$ mass matrix and this, effectively, makes the 3×3 CKM matrix non-unitary. Clearly, much experimental and theoretical work still awaits us before it can be said that we understand the phase structure in the flavor sector. If some discrepancies from the CKM expectations were to be found in B decays, looking at processes like $B_d \to K_S K_S$, which is a pure $b - s$ Penguin decay (and thus should have zero asymmetry) might be a good diagnostic[28].

4. The mysteries

There were a number of talks in the Conference which addressed important and still mysterious structural issues in particle physics, like supersymmetry and supersymmetry breaking and neutrino masses and mixing. I have decided not to attempt to summarize these talks here because they either were not quite germane to the main topic of the Conference or they were given too near to my own concluding talk to sensibly be able to report on them. I would like, however, to end by discussing two topics briefly which are both germane to CP violation and where the issues remain quite open and challenging. These concern: baryogenesis at the electroweak scale, which was addressed here by Shaposhnikov[38], Dine[39] and Yanagida[40], and the strong CP problem of which various aspects of it were discussed in the Conference by Vainshtein [41], Kikuchi[42], Branco[37] and Schierholz[43].

There are a number of issues which are widely agreed upon concerning electroweak baryogenesis and before I try to outline where the controversies reside, it might be useful if I summarized these non-controversial points first. The standard model possesses 2 of the Sakharov conditions[3] necessary for baryogenesis: it violates C and CP and it violates baryon number, B. The violation of baryon number in the standard model is a quantum effect[44] and is the result of a chiral anomaly[45] in the (B+L)–current. Since this current is carried by all the quarks and leptons, there is a selection rule governing (B+L)–violating processes relating the total change in this quantity to the number of generations N_g (presumably $N_g = 3$):

$$\Delta(B+L) = 2N_g\ .$$

Since $2N_g$ is also the possible amount by which the topological index of the electroweak gauge field vacuum configurations changes by, (B+L)–violating processes in the standard model involve non-trivial changes in these configurations. At zero temperature, these gauge field vacuum changes are strongly suppressed by a tunneling factor[44] and baryon number violation is vanishingly small ($\Gamma_{\rm B+L\ viol.} \sim \exp\ -4\pi/\alpha_W$, with $\alpha_W = \alpha/\sin^2\theta_W \sim 1/30$). However in a temperature bath–like in the early universe–these gauge field vacuum changes can occur via thermal fluctuations, and the rate for (B+L)-violation can become important. This was the crucial observation of Kuzmin, Rubakov and Shaposhnikov[46]. One

finds, in fact, a rate for (B+L)-violation that is suppressed by a Boltzmann factor below the temperature of the electroweak phase transition and is unsuppressed above[39][38]:

$$\Gamma_{\text{B+L viol.}} \sim \begin{cases} e^{-E_{\text{sph}}(T)/T} & T < T_c \\ (\alpha_W T)^4 & T > T_c \end{cases}$$

Here $E_{\text{sph}}(T)$ is, roughly, the height of the barrier separating the two gauge vacua and is related to the electroweak order parameter:

$$E_{\text{sph}}(T) \sim M_W(T)/\alpha_W \sim \langle\phi(T)\rangle/g_2 \ .$$

A comparison of the above rate to the rate of expansion of the universe, given by the Hubble constant at tempeature T ($H \sim T^2/M_{\text{Planck}}$), shows that, as a result of standard model interactions, (B+L)-violating processes are in equilibrium ($\Gamma_{\text{B+L viol.}} > H$) during a large temperature interval in the universe:

$$T^* \sim 10^2\text{GeV} \leq T \leq T_{\text{max}} \sim 10^{12}\text{GeV} \ .$$

During this period, any primordial (B+L)-asymmetry in the universe will be erased[46]. This phenomena has obviously a direct bearing on the presently observed B-asymmetry in the universe and suggests two different alternatives:

i) The observed B-asymmetry ($\eta_B \sim 4 \times 10^{-10}$) is a result of a primordial (B-L)-asymmetry (or of a primordial L-asymmetry, as in the model discussed by Yanagida[40] at this Conference) which is not affected by standard model processes.

ii) There is no primordial (B-L)-asymmetry and since any primordial (B+L)-asymmetry is erased during the evolution of the universe, the observed B-asymmetry must be generated at the electroweak phase transition.

The talks of Dine[39] and Shaposhnikov[38] here concentrated on this second very intriguing possibility. To generate η_B at the electroweak phase transition, three conditions need to hold. First, the electroweak transition must be first order, so that the last Sakharov[3] condition for baryogenesis–that baryon number violating proceseses must be out of equilibrium–is satisfied. However, at the electroweak phase transition one must, in addition, make sure that this transition is sufficiently **strongly** to first order, so that the generated asymmetry is not subsequently erased. This second condition requires that $\Gamma_{\text{B+L viol.}}(T^*) < H(T^*)$, which will obtain provided $E_{\text{sph}}(T^*)/T^*$ is sufficiently big. Numerically[39] this requires

$$\langle\phi(T^*)\rangle/T^* \geq 1 \ .$$

Finally, one must also require that the true-vacuum nucleation during the phase transition is both sufficiently efficient, and sufficiently **fermion-antifermion asymmetric** (this is where CP violation enters into the problem), so that the resulting η_B produced is big enough. This is the most tricky part, requiring a real calculation of the kinetics of the problem.

It is in these last two points where there is not full agreement in the literature–a disagreement which was exemplified here by the two different points of view expressed by Dine[39] and Shaposhnikov[38]. Using the finite temperature effective potential $V_{\text{eff}}(\phi, T)$ for the standard model Higgs sector one can calculate $\langle\phi(T^*)\rangle/T^*$. As pointed out long ago by Shaposhnikov and collaborators [47], $\langle\phi(T^*)\rangle/T^*$ will only be large provided one has a light Higgs boson in the theory. Conversely, using the bound on the Higgs mass provided by LEP ($M_H > 62.5$ GeV[48]), from a calculation of $V_{\text{eff}}(\phi, T)$ one can obtain an upper bound for $\langle\phi(T^*)\rangle/T^*$. Recent calculations of $V_{\text{eff}}(\phi, T)$[49] for the case of one Higgs doublet using the LEP bound give $\langle\phi^*(T)\rangle/T^* \leq 0.5$. This led Dine[39] to conclude that one cannot generate the baryon asymmetry at the electroweak scale in this simplest model of symmetry breakdown.

Shaposhnikov[38] disagreed with this conclusion for two reasons. First, he did not trust the calculation of $V_{eff}(\phi, T)$ because of infrared problems. Second, he believes that for this dynamical problem it does not suffice to compute $\langle\phi(T^*)\rangle/T^*$ via an effective potential, but one must really compute directly $\Gamma_{\text{B+L viol.}}(T^*)$. I believe the first objection is not that germane, at least for the region of Higgs masses in question. However, the second point may well be relevant. In this case it may be premature to imagine that

there is a conflict between electroweak baryogenesis and a one Higgs doublet model of symmetry breaking.

The second area of disagreement between Dine and Shaposhnikov is more technical and is connected with the actual mechanism by which a fermion number asymmetry is generated at the electroweak phase transition. Roughly speaking, as a bubble of true-vacuum nucleates during the phase transition, the bubble wall because of CP violating interactions will have different transmission coefficients for fermions and antifermions. The net baryon asymmetry η_B is proportional to the difference in transmission rates for baryons and antibaryons at the bubble wall. Dine[39] argued that this rate difference in the CKM model–as in the vacuum–is irrelevantly small (of $O(10^{-22})$) because it is totally GIM suppressed. One finds:

$$\begin{aligned} \eta_B \quad &\sim \quad \left[(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)\right. \\ &\times \quad (m_b^2-m_s^2)(m_b^2-m_d^2)(m_s^2-m_d^2) \\ &\times \quad \left. s_{12}s_{23}s_{13}\sin\delta\right]\frac{1}{M_W^{12}} \ . \end{aligned}$$

Shaposhnikov[38], on the other hand, argues that in a thermal bath the GIM factor is largely erased, so that in the standard model one can in fact obtain a sizeable asymmetry. Although I cannot really judge whether the calculation of η_B presented by Shaposhnikov (based on the work of Farrar and Shaposhnikov [50]) is reliable, it seems likely to me that thermal effects can help ameliorate the GIM suppression one naively calculates.

My own conclusion regarding electroweak baryogenesis is that it is unlikely that it actually proceeds in the simplest model of symmetry breaking. With one Higgs doublet, the electroweak phase transition is probably not sufficiently strongly first order to prevent sizable erasure of the produced asymmetry. Furthermore, this asymmetry is already probably too small due to having too simple a source for CP violation. However, in extended Higgs models, both of these difficulties are ameliorated. Hence, if the baryon asymmetry in the universe was produced at the electroweak scale, one should expect to have other sources of CP violation, besides the CKM phase be relevant at low energies. Thus electroweak baryogenesis and an edm in the 10^{-26} ecm range may well be closely connected!

Let me end by making a few remarks on the strong CP problem. The presence of the term

$$\mathcal{L}_{\text{strong CP}} = \bar{\theta}\frac{g_3^2}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{a\mu\nu} \ ,$$

with $\bar{\theta}$ being the sum of the QCD vacuum angle θ and the contribution from the quark mass matrix

$$\bar{\theta} = \theta + \arg\det M \ ,$$

follows from a careful examination of the correct vacuum structure of QCD[51]. Although one can try to avoid the appearance of the strong CP interaction by modifying the $|\theta>$- vacuum structure of QCD, as it has been suggested recently by Samuel[52], one then gets back into trouble with the old U(1) problem that $m_\eta \neq \sqrt{3}\ m_\pi$! This is basically the criticism presented here by Kikuchi[42] to the "solution" to the strong CP problem of Samuel. The renormalization properties of $\bar{\theta}$ discussed in the talk by Vainshtein[41] made it apparent that in all aspects this parameter acts precisely as would the coefficient of any dimension 4 operator. The concomitant GIM factors which entered in Vainshtein's discussion are also totally natural, since as any quark becomes massless it is necessary that $\bar{\theta} \to 0$[53].

Unfortunately, these comments do not bring one closer to a solution to the strong CP problem. The present bounds on the neutron edm require that $\bar{\theta} < 10^{-9} - 10^{-10}$[54] and there is no immediate explanation why this effective angle should be so small. Of course, I am still prejudiced towards the solution to this problem which I proposed with Helen Quinn some time ago [55]! However, one has no proof as yet for the presence of a $U(1)_{PQ}$ global symmetry since no axions (visible or invisible) have been found. In my view, the PQ solution is preferable to solutions of the strong CP problem involving soft CP breaking, since models of this type run into a variety of difficulties unless one is very careful. This was nicely illustrated at this Conference by the example discussed by Branco[37].

The difficulties which soft CP breaking models encounter are different depending on whether the breaking of CP occurs at low scales (i.e. near the electroweak scale) or at high scales (i.e. near a GUT scale). In the first case, as in the model Branco discussed, one has problems with the enormous energy density that resides in the walls separating domains in the universe, which vastly exceeds the universe's closure density[56]. If CP is broken spontaneously at high scales, one can avoid this domain wall problem through inflation. However, then it is difficult to transmit the CP violating phase generated at the high scale to the low energy sector [57]. The most successful models of this type have been devised by Nelson and by Barr[58] and, in general, tend to be of a superweak variety. Therefore, if these ideas are correct one would expect quite different predictions for CP violation in the B system!

These brief comments on electroweak baryogenesis and on the strong CP problem emphasize an important lesson, which is worthwhile keeping in mind. Namely, that even though the elucidation of some of the deep mysteries may perhaps escape us theoretically at the moment, new experimental data can have a profound impact on our understanding. Indeed, new data may expose our present beliefs only as theoetical prejudices. Let us hope that future experiments probing for CP violation may have this salutary effect!

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